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MECHANICS OF MULTIFUNCTIONAL MATERIALS & MICROSYSTEMS

9 March 2012

***B. L. ("Les") Lee, ScD
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AFOSR/RSA***

Air Force Research Laboratory

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 09 MAR 2012		2. REPORT TYPE		3. DATES COVERED 00-00-2012 to 00-00-2012	
4. TITLE AND SUBTITLE Mechanics Of Multifunctional Materials & Microsystems				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory, Wright-Patterson AFB, OH, 45433				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Presented at the Air Force Office of Scientific Research (AFOSR) Spring Review Arlington, VA 5 through 9 March, 2012					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 50	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			



2012 AFOSR SPRING REVIEW



NAME: *B. L. (“Les”) Lee*

BRIEF DESCRIPTION OF PORTFOLIO:

*Basic science for **integration** of **emerging materials** and **micro-devices** into future Air Force **systems** requiring **multi-functional design***

LIST OF SUB-AREAS:

*Fundamentals of **Mechanics** of Materials;
Life Prediction (Materials & Micro-devices);
Sensing, Detection & Diagnosis;
Multifunctional Design of **Autonomic** Systems;
Multifunctional Design of **Reconfigurable** Systems;
Self-Healing & Remediation;
Self-Cooling & Thermal Management;
Energy Management for Self-Sustaining Systems;
Actuation & Threat Neutralization;
Engineered Nanomaterials*



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***Self-Cooling** & Thermal Management; →*
***Energy** Management for Self-Sustaining Systems; ↘*
***Actuation** & Threat Neutralization; ↗*
Engineered Nanomaterials ↘



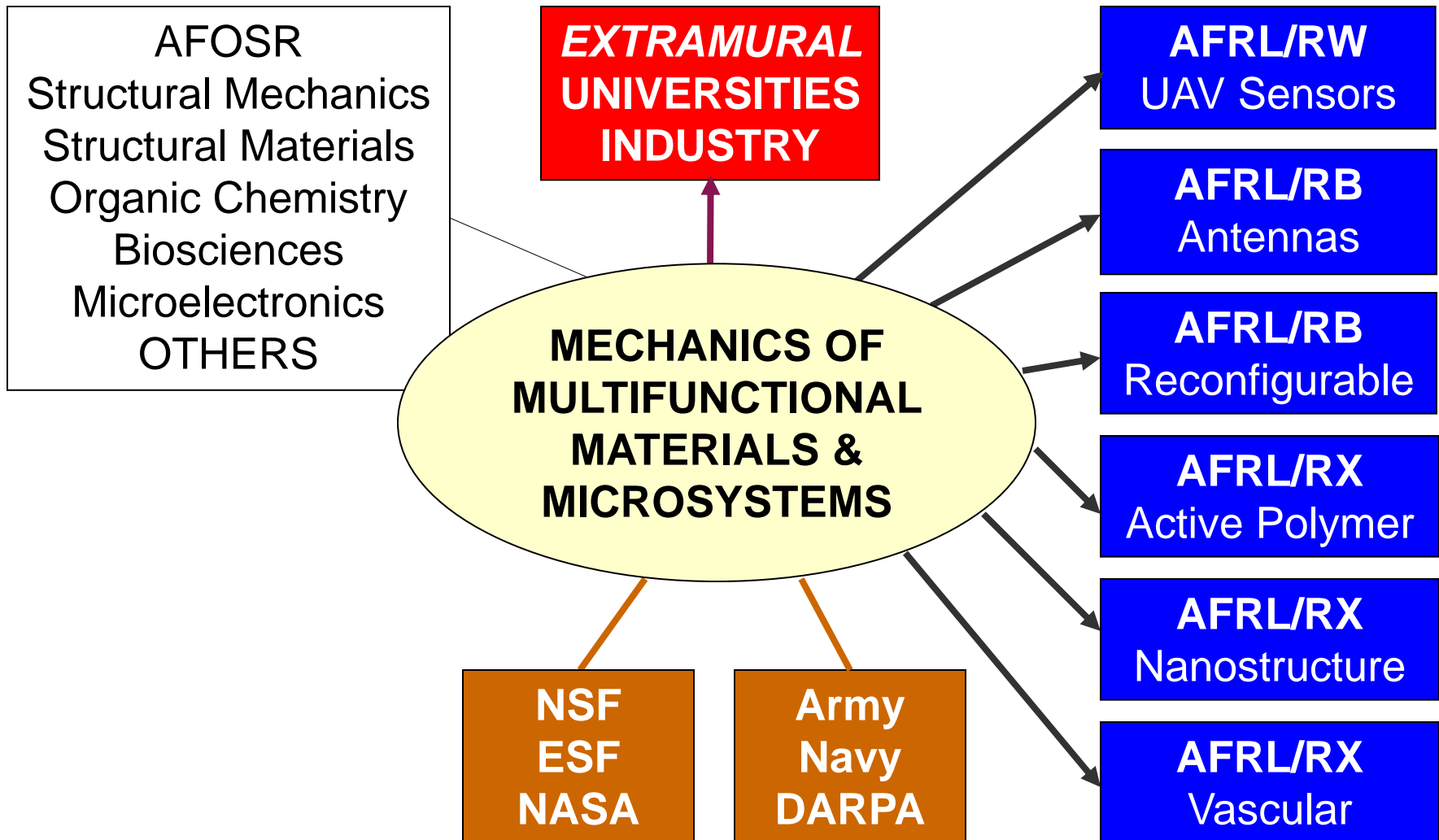
SCIENTIFIC CHALLENGE



- **Self-healable** or **in-situ remendable** structural materials
(1st-ever program; world lead)
- Microvascular composites for **continuous self-healing** and **self-cooling** systems *(1st-ever program; world lead)*
- Structural integration of **energy harvest/storage** capabilities *(1st-ever program on structurally integrated multiple energy harvest capabilities; DoD lead)*
- Neurological system-inspired **sensing/diagnosis/actuation** network *(pot'l world lead)*
- Mechanized material systems and micro-devices for **reconfigurable** structures *(DoD lead)*
- **Experimental** nano-mechanics *(DoD lead)*
- Active materials for **threat neutralization** *(planned)*

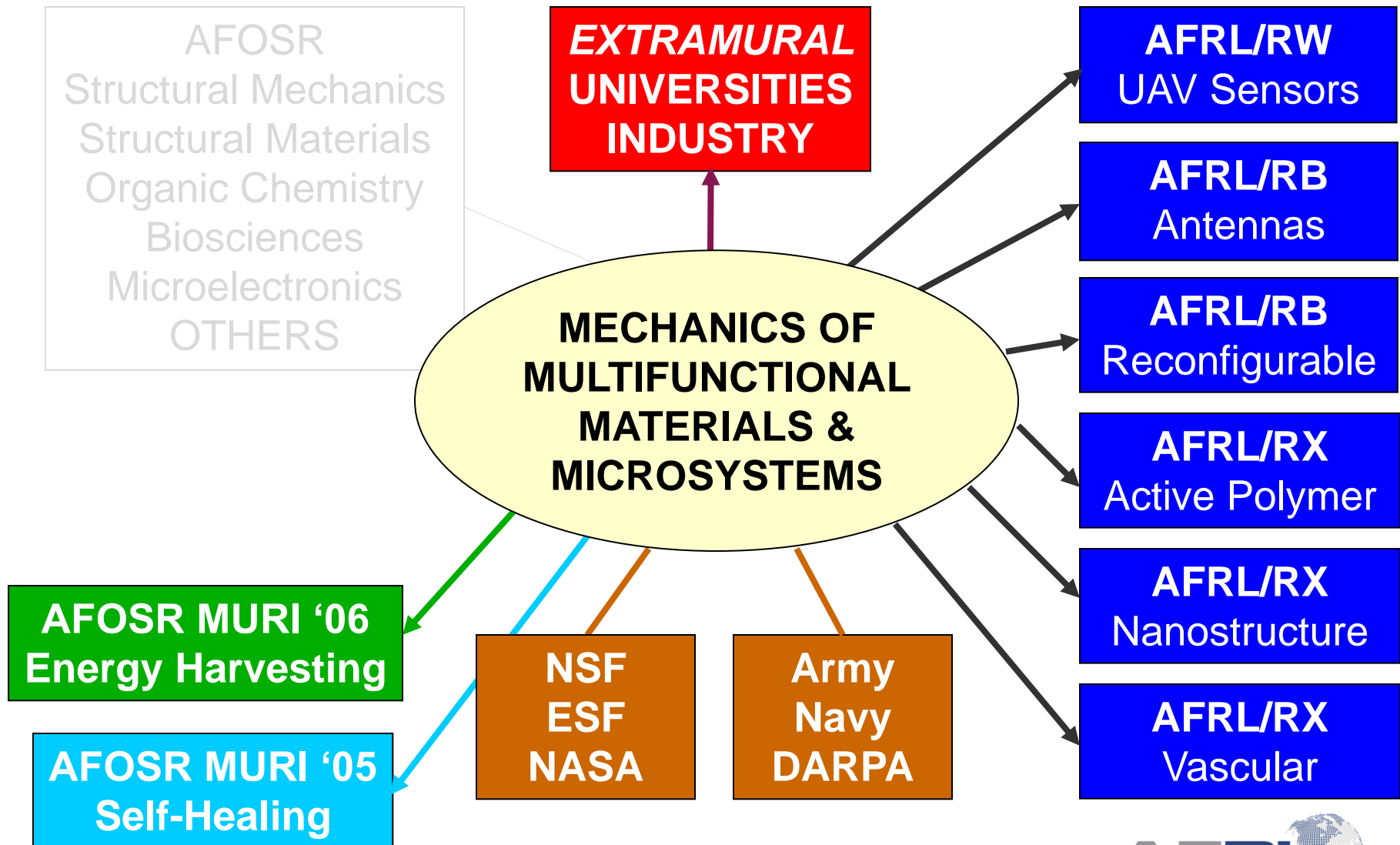


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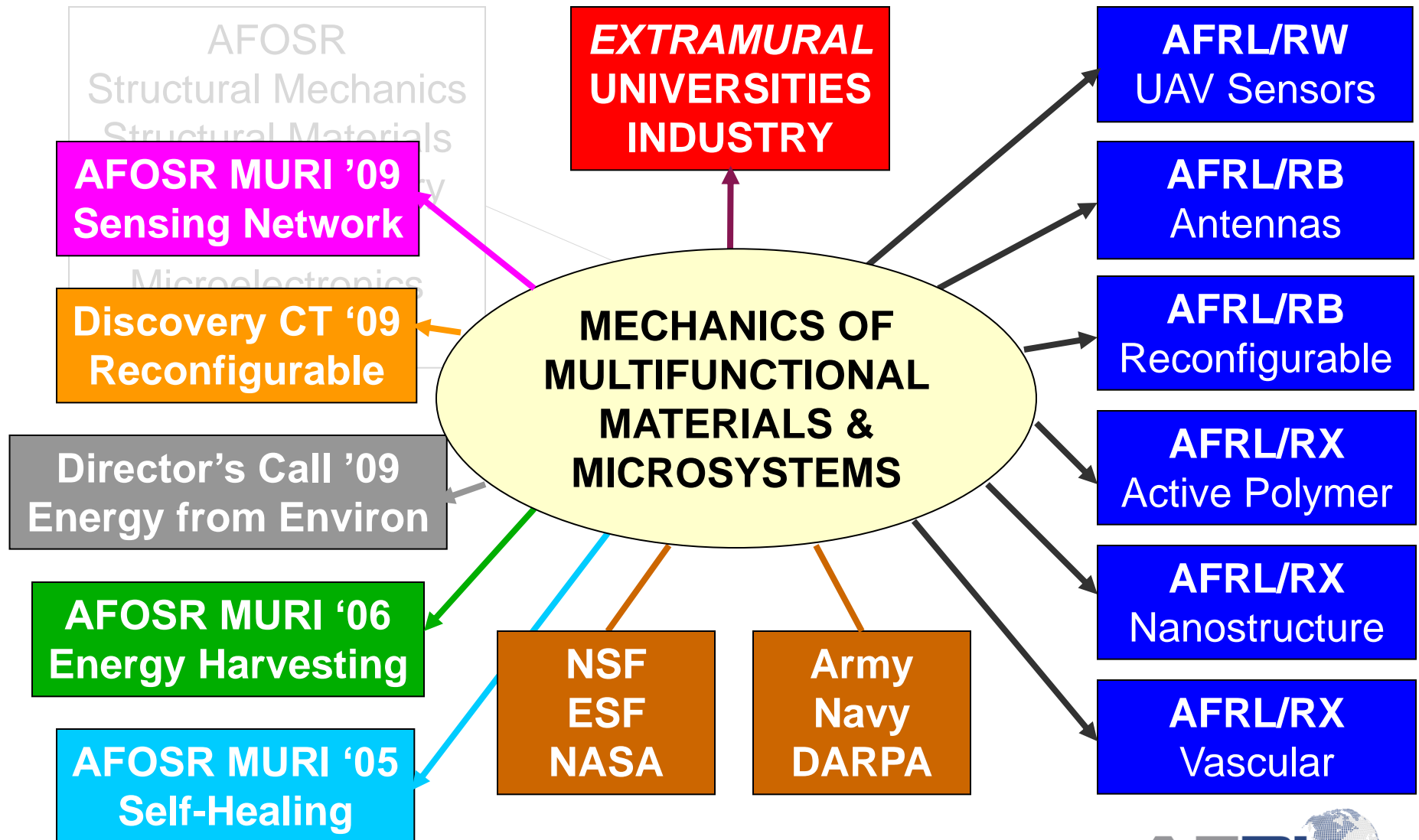


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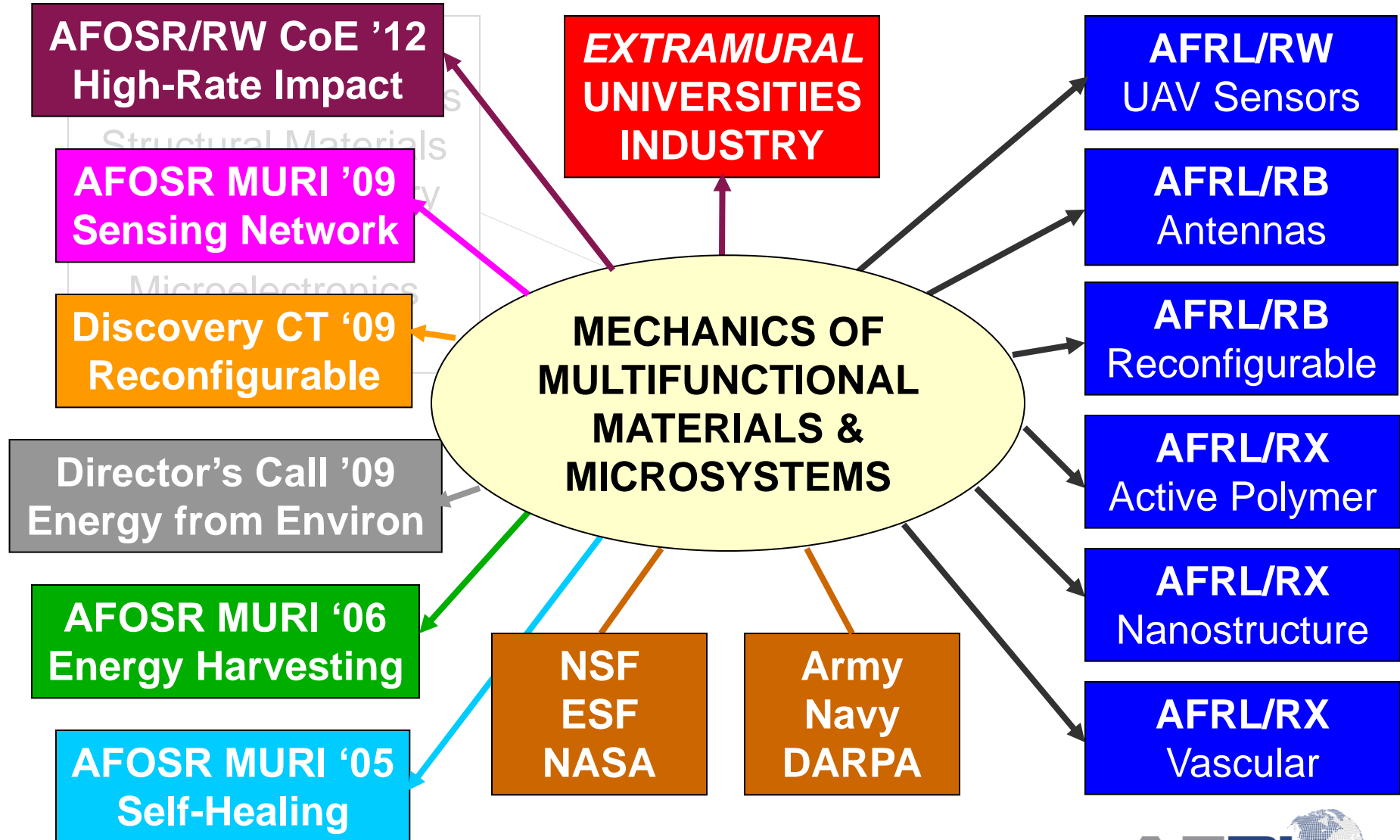


PROGRAM INTERACTION





PROGRAM INTERACTION





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[^] YIP; ^{*} CoE



2012 AFOSR SPRING REVIEW



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BRIEF DESCRIPTION

Basic science
into future

LIST OF SUBJECTS

**Fundamental
Life Prediction**

Sensing, Detection

Multifunctional

Multifunctional

Self-Healing

Self-Cooling

Energy Management

Actuation

Engineering

Subject:

- < **Multi-scale Simulation of Interfacial Phenomena**
Deformation & Fracture of Silicon for MEMS
 - > **Damage-tolerant Biological Composites**
- > **Designing Structures for Functional Materials**
- > **High-rate Physics of Heterogeneous Materials**

> **New**; < **Concluded**

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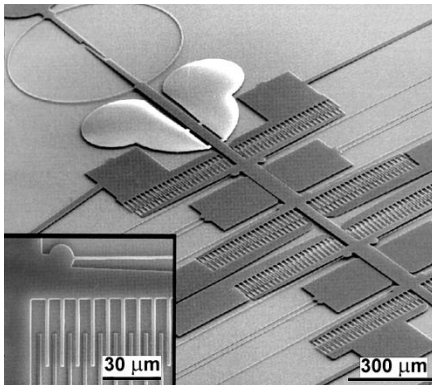
FRACTURE OF MEMS MATERIALS

(UIUC: Chasiotis)

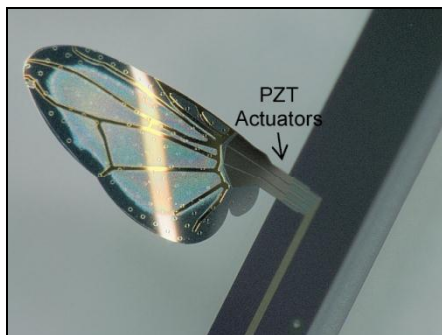


Polycrystalline silicon is most widely used for MEMS

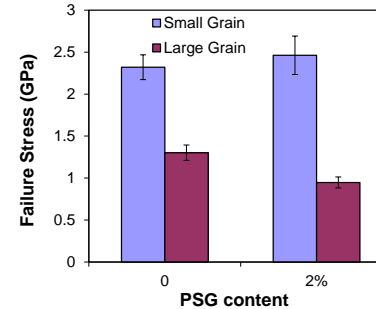
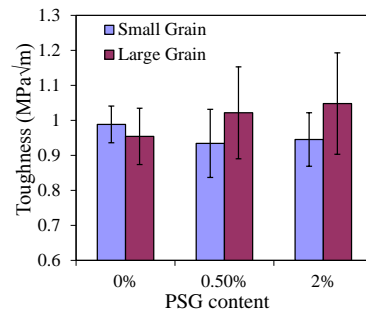
- Experiments (bi-crystal Chevron) show the role of **grain structure** in fracture of polysilicon.
- Fracture of polysilicon is **intra-granular** due to high grain boundary strength.



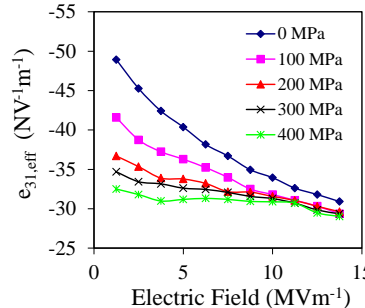
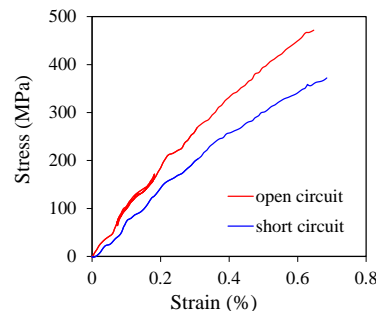
PZT thin film bimorph actuates a millimeter scale wing for MAV



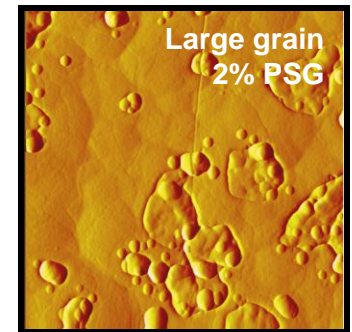
- Mode I fracture toughness of **large grain polysilicon** increased with the amount of Phosphorus **doping**. Dopants at grain boundaries may allow for **local crack deflection**.
- The fracture strength of **"laminated" small grain polysilicon** was **80-150% higher** than large grain polysilicon with doping playing a secondary role in fracture strength. Fabrication of polysilicon in laminate form reduced the **flaw size** significantly.



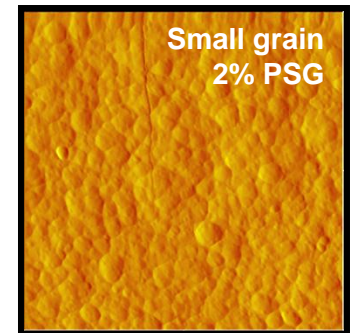
- The modulus and tensile strength of **PZT films** for MEMS were measured for the first time. They were **30% smaller under short circuit conditions** as opposed to open circuit conditions.
- The high bias voltage **electroactive coefficient** varied nonlinearly with the electric field, but it **became independent of the applied field at high pre-stress values**.



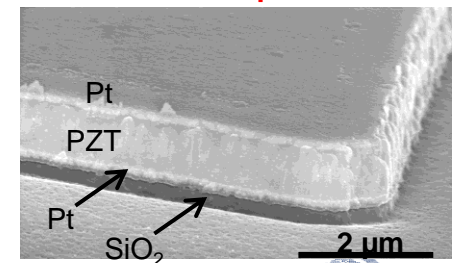
Polycrystalline Silicon



500 nm



PZT Composites





AFOSR/RW CO-SPONSORED COE'12 (RW: Chhabildas)

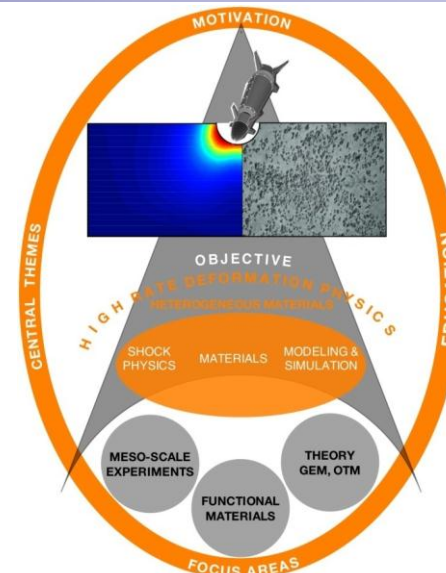
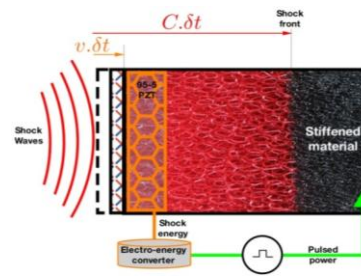
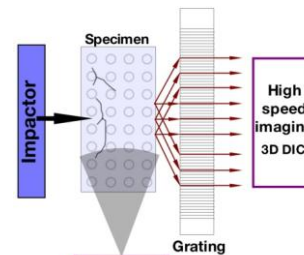
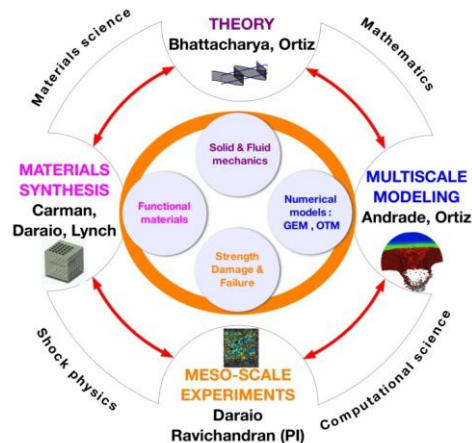


University Center of Excellence:
High-Rate Deformation Physics of Heterogeneous Materials
California Institute of Technology & University of California, Los Angeles



Goals:

- Develop a fundamental understanding of the deformation physics of heterogeneous materials at **high-strain-rates** and **high-pressures**
- Develop **microstructures** and **functional nano-materials** for mitigating shock and damage
- Use innovative methods for **educating** and **training** the next generation of scientists and practitioners



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Francesca Scire (Phys Sci)+

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Subject:

Electromagnetically Tunable Fluids
Thermal Signature Reduction & EMI Shielding
< Nanocomposites for Sensing & Actuation
Damage Detection w Time Domain Reflectometry
Bio-inspired Intelligent Sensing Materials

Embedded Sensors & Actuators for MAV

“

“

> Load-Bearing Antennas of Conductive Textiles

“

“

> New; < Concluded

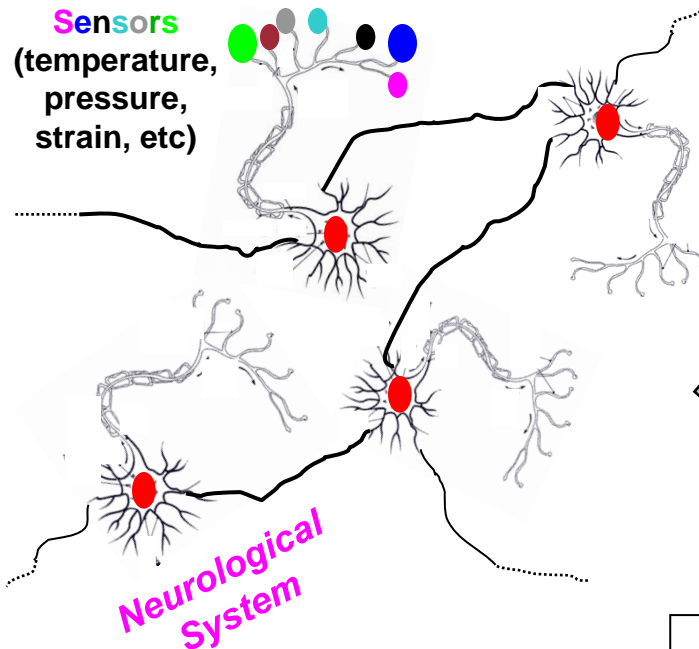
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MURI '09

BUILT-IN SENSING NETWORK (Stanford/U CO/UCLA/NYIT: Chang)



Local neurons
(processor, memory, communication devices)

Synapse:

Cognition and decision-making are determined by a relative level of cumulative signal strength with respect to the synapse threshold values

Biological sensory systems rely on **large numbers of sensors** distributed over **large areas** and are specialized to detect and process **a large number of stimuli**. These systems are also capable to **self-organize** and are **damage tolerant**.

Multi-Scale Design, Synthesis & Fabrication

Bio-inspired Sensor Network

Stretchable Matrix

Synaptic Circuits

Autonomous System

Sensor Network for Structural Integration



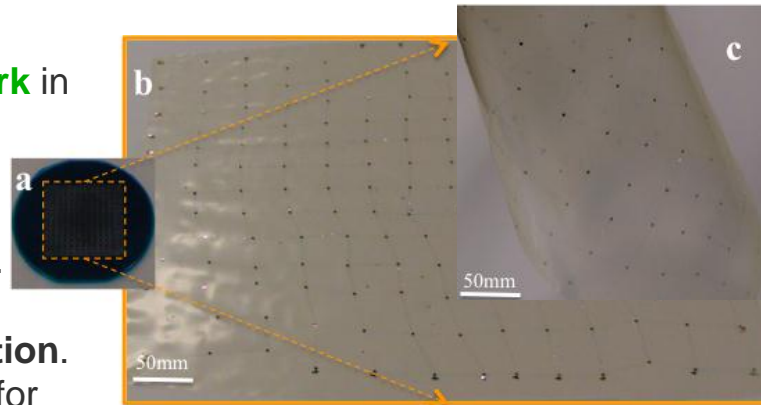
Task 1: Sensor Network for Structural Integration

To develop a nano/micro-scaled sensor network, functionalize the network to a macro scale, and integrate the sensor network into composite materials.

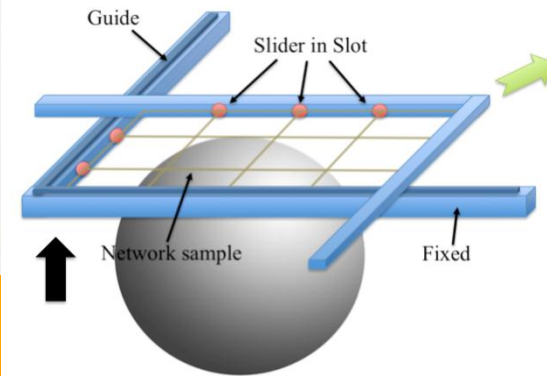
Chang's group

To develop **PZT sensor network** in a CMOS-like foundry:

- Scaled down sensor network to **reduce wire & node size** (for higher spatial resolution).
- Developed spin-coated-on process for **network fabrication**.
- Developed a design method for **network expansion**.



13 by 13 stretchable temperature sensor network

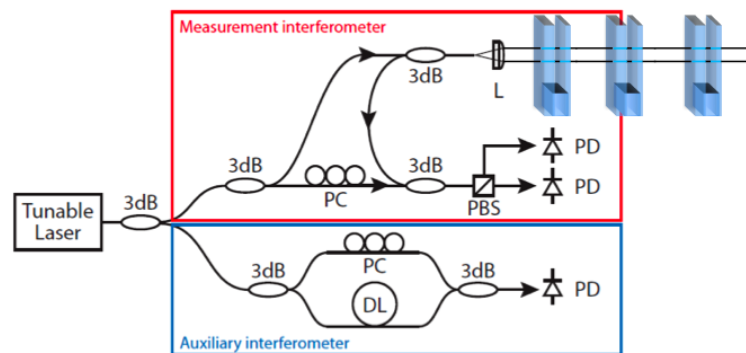


Conceptual design of test bed

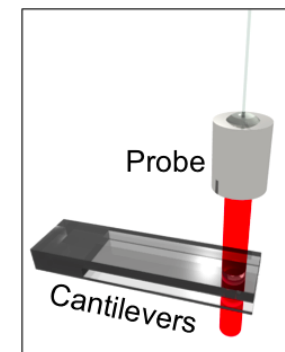
McLeod's group

To develop ultra-precise **polymer optical sensor network** via **liquid deposition photolithography**:

- Deposition of polymer from the liquid state enables tightly integrated optical sensors.
- Atomic-scale precision: **0.53 nm**
- Interrogates thousands of sensors through **round-trip delay** to each partially-reflecting surface.



Precision Optical Frequency Domain Reflectometry



Self-referenced transducer

Micro/Nano Sensors for State Awareness

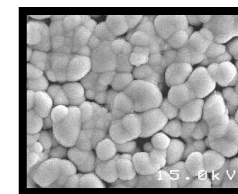
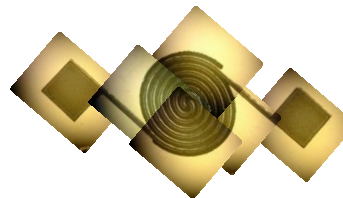


Task 2: Micro/Nano Sensors for State Awareness

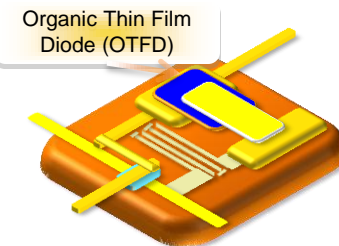
To develop multi-physics multi-scale sensors for state awareness with an ease of network integration.

Chang's group:

- Screen-printing **PZT sensors** onto a network
- Integrated **organic thin film diodes** into sensor network



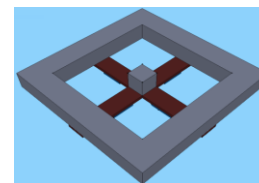
SEM image of good screen printed PZT



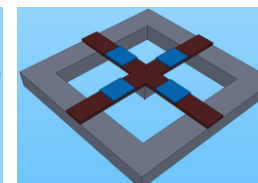
Organic Thin Film Diode (OTFD)

Wang's group:

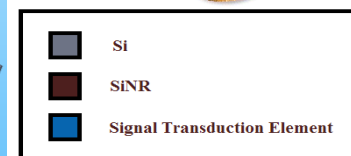
- Designed an **air flow sensor** measuring the direction and the velocity.
- Used four anisotropic **magnetostrictive** structures to transduce an air flow-induced beam deflection into a resistance change.



Top View

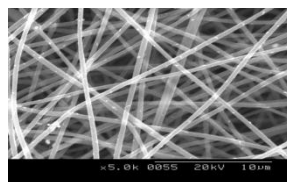


Bottom View

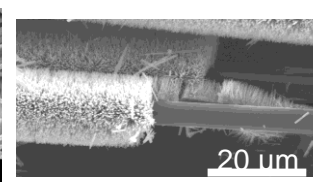


Ko's group:

- Developed multi-functional **nanofibers** that can serve as: **magnetic**, **piezo-electric** and **chemical sensors**

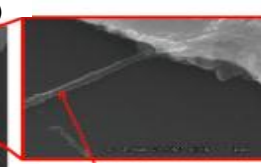
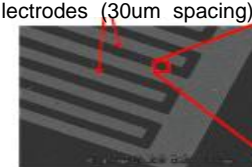


Magnetic nanofibers



Piezoelectric fibers

Electrodes (30um spacing)



Single fiber (d=90nm)

Nanofiber-based chemical sensors

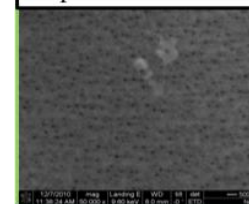
Carman's group:

- Investigated nano-structured **magneto-electric** materials for detecting **magnetic fields**.
- 40 and 25 nm diameter Ni nanostructures fabricated using AAO and DBC nanotemplate respectively.

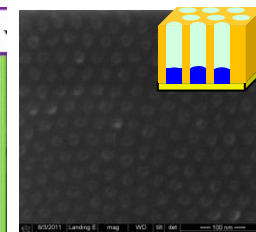
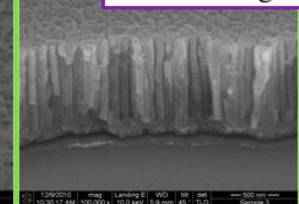
McLeod's group:

- A new approach to **optical sensor** interrogation.

Top view of AAO



45° tilted angle



DBC Polymer template

Bio-inspired Neuron Circuits & Interface Electronics

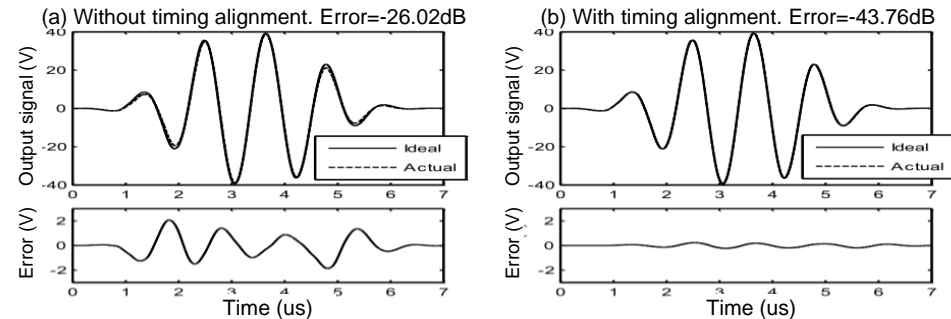


Task 3: Bio-inspired Neuron Circuits and Interface Electronics

To develop bio-inspired neuron circuits with appropriate electronics to interface with various sensors.

Murmann's group

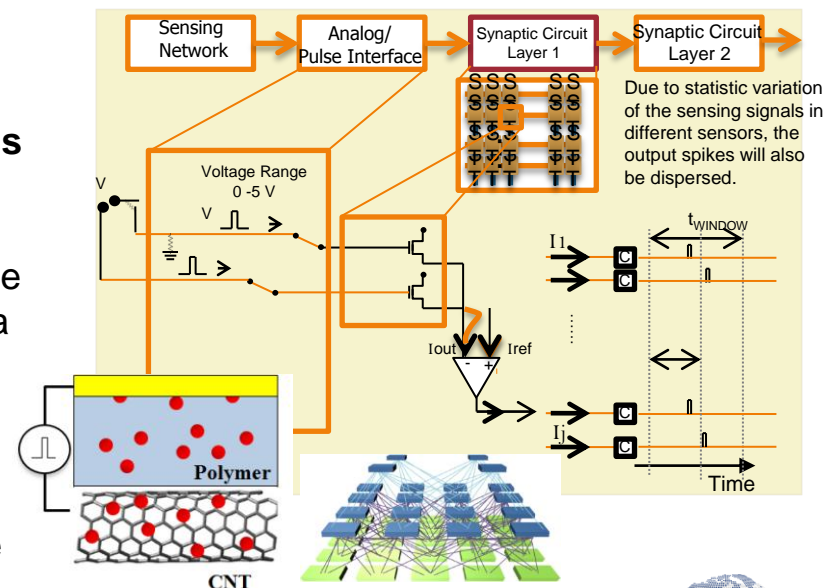
- Built a dense **integrated interface circuit** for ultrasonic sensing of the structural state.
- Defined **piezo driver** test chip to deliver a high voltage, high freq, continuous-time waveform.
- Plans to integrate piezo sensing interface with piezo driver on a **single chip**.



Output signals of the piezo-element driver without (left) and with (right) timing alignment

Chen's group

- Invented **synaptic transistors** with dynamic logic, memory, and learning functions by integrating ions in CNT/polymer composites.
- Voltage pulses can induce the **electrochemical reactions between ions and CNTs**, modifying the conductivities of CNTs reversibly for learning and memory functions.
- A **neuron circuit** with a large number of **synapses** can be fabricated by integrating an analog Si-CMOS circuit and a randomly connected CNT network in polymer composite.
- Integrated the first time the **synaptic transistors** with a **stretchable network** (from *Chang's group*) to process signals from an array of **temperature sensors**.
- Demonstrated that the integrated circuits can process the **temperature profile** dynamically.





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Scott White (UIUC)

Jeffrey Moore (UIUC)

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Scott White (UIUC)*

*Jeffrey Moore (UIUC)**

*Nancy Sottos (UIUC)**

*Jennifer Lewis (UIUC)**

*Philippe Geubelle (UIUC)**

*Kenneth Christensen (UIUC)**

*Jonathan Freund (UIUC)**

Jeff Baur (AFRL/RXBC)

Tom Darlington (Nanocomposix)+

Tony Starr (SensorMetrix)+

*** MURI; + STTR**



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Basic science research
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LIST OF SUBJECTS

Fundamental

Life Prediction

Sensing, Detection

Multifunctional

Multifunctional

Self-Healing

Self-Cooling

Energy Management

Actuation

Engineering

Subject:

< **Thermally Remendable Composites**
Interfacial Self-Healing in Composites
Regeneration & Remodeling of Composites

> **Self-Assembly and Self-Repair of Structures**
< **Microvascular Autonomic Composites**

< **Processing of Microvascular Structures**
Remendable Composites w Resistive Heating

> **New**; < **Concluded**

PI's & Co-PI's:

Sia Nemat-Nasser (UC San Diego)

Nancy Sottos (UIUC)

Scott White (UIUC)

Jeffrey Moore (UIUC)

Nicolaus Correll (U CO)

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Jennifer Lewis (UIUC)*

Philippe Geubelle (UIUC)*

Kenneth Christensen (UIUC)*

Jonathan Freund (UIUC)*

Jeff Baur (AFRL/RXBC)

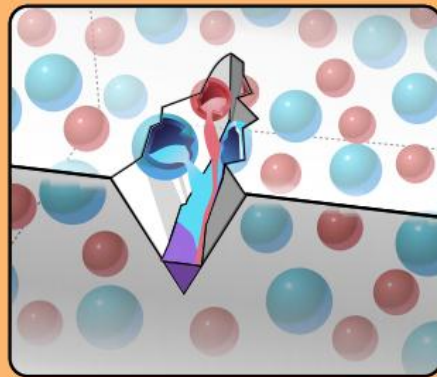
Tom Darlington (Nanocomposix)+

Tony Starr (SensorMetrix)+

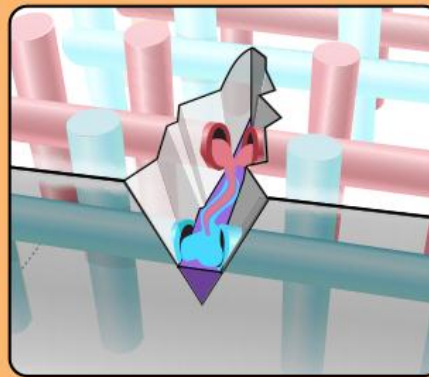
* **MURI**; + **STTR**



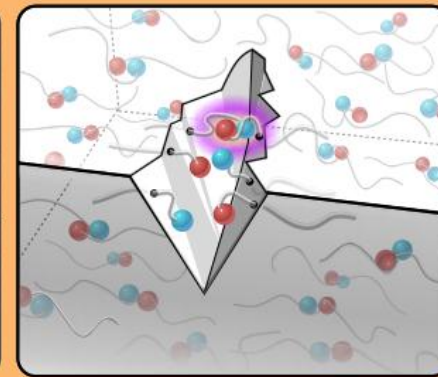
THREE APPROACHES FOR SELF-HEALING



(a) Capsule-based

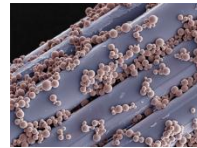
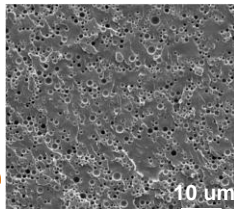


(b) Vascular



(c) Intrinsic

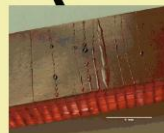
Nature



Natural Models

MURI '05

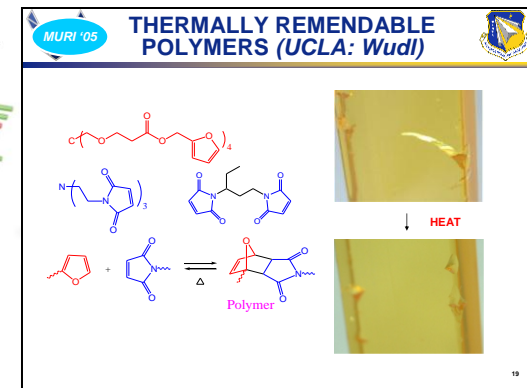
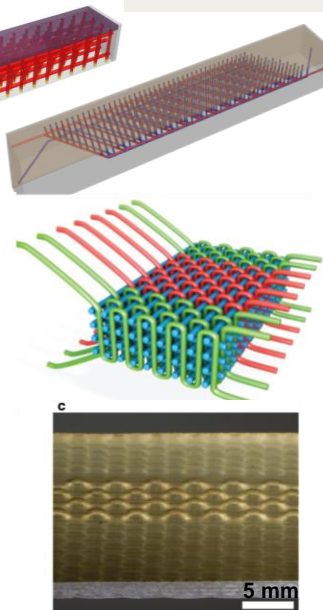
Engineering Design



Functional Testing



Synthetic Reproduction





STRUCTURAL REGENERATION (UIUC: White/Moore)



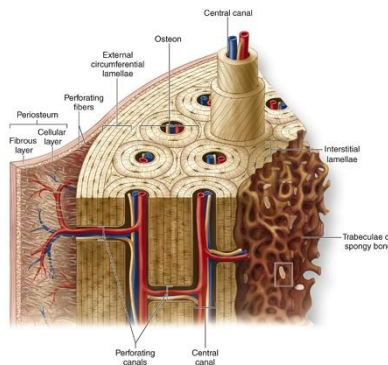
Regeneration and Remodeling in biology:

Tree skink lizard



Linckia starfish

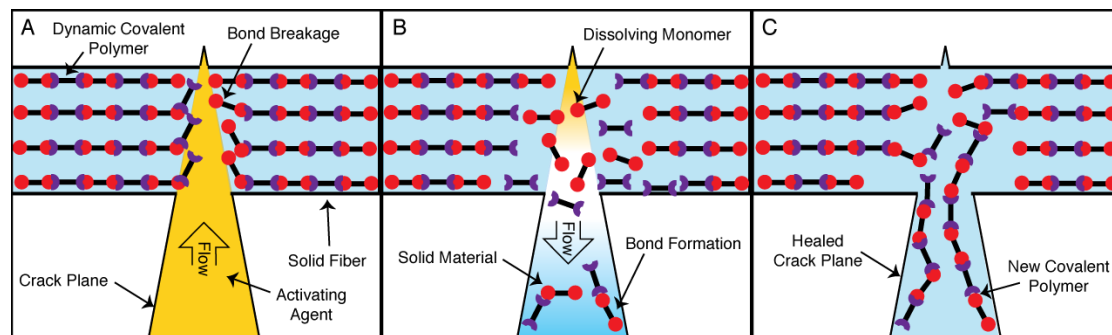
Human Bone



Conventional Material Systems:

- Passive materials not responsive to degradation
- Not adaptive to loading conditions
- Manual repair of damage
- Overdesign to account for reduction in mechanical properties and varied loading conditions

New approach: *Dynamic polymers + inert scaffolds*



- Synthesized two types of **dynamic covalent bond based polymer** systems which can be **reversibly changed from liquid to solid and vice versa**
- **Poly(vinyl alcohol)** and **borate ions** undergo multiple **sol-gel** transitions under controlled pH
- **Reversible gel formation** of a functionalized poly(ethylene glycol) and crosslinker

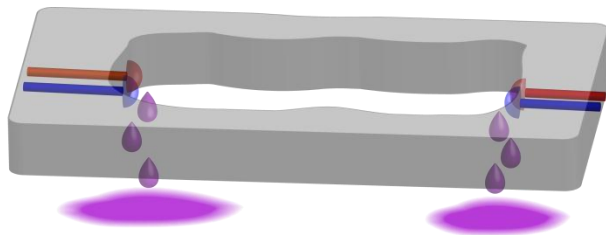


STRUCTURAL REGENERATION: *Large Volume Damage*

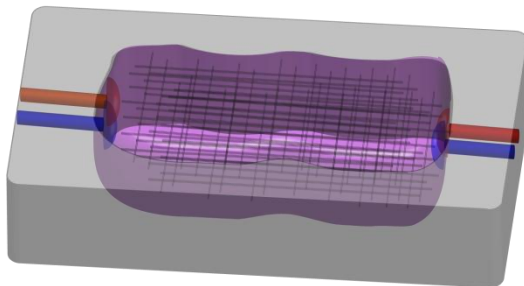


Background:

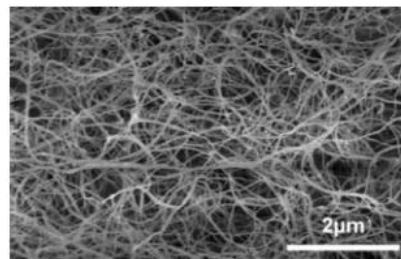
- Repair volume is limited by surface tension



- Self-assembled scaffolds** will provide temporary support as healing agents delivered



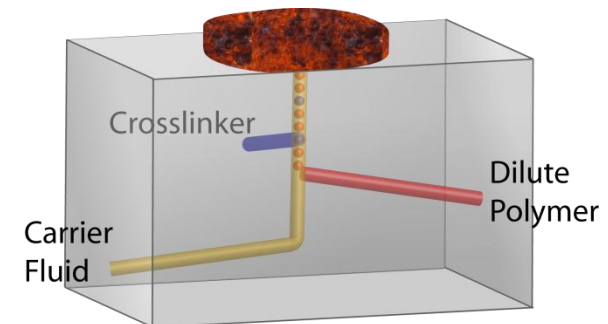
Scaffold-supported
damage region



Peptide Amphiphile
Self-assembling Fibers

Progress:

- Sol-Gel transition** allowed three orders of magnitude stiffness increase
- Scaffold formation based on **peptide amphiphile hydrogels** is repeatable for multiple cycles
- Aggregate scaffolds formed by **hydrogen, covalent or ionic bonds** in progress
- Isolated constituents delivered via **vascular network**





2012 AFOSR SPRING REVIEW



NAME: *B. L. ("Les") Lee*

BRIEF DESCRIPTION OF PORTFOLIO:

Basic science for integration of emerging mater into future Air Force systems requiring multi-fu

LIST OF SUB-AREAS:

*Fundamentals of Mechanics of Materials;
Life Prediction (Materials & Micro-devices);
Sensing, Detection & Diagnosis;
Multifunctional Design of Autonomic Systems;
*Multifunctional Design of Reconfigurable System
Self-Healing & Remediation;
Self-Cooling & Thermal Management;
*Energy Management for Self-Sustaining System
Actuation & Threat Neutralization;
Engineered Nanomaterials***

PI's & Co-PI's:

Abraham Stroock (Cornell U)
Noel Holbrook (Harvard U)
Vikas Prakash (Case Western)
Patrick Kwon (Mich St U)
George Lesieutre (Penn St U)
Aaron Esser-Kahn (UC Irvine)^
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Kenneth Christensen (UIUC)*
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Ajit Roy (AFRL/RXBT)

^ YIP; * MURI



2012 AFOSR SPRING REVIEW



NAME: B

BRIEF DE

Basic sci
into futur

LIST OF S

Fundame

Life Pred

Sensing,

Multifunc

Multifunc

Self-Heal

Self-Cool

Energy M

Actuation

Engineer

Subject:

Plant-mimetic Heat Pipes

**< CNT Based Thermal Interface Materials
New Generation of Perspirable Skin**

Variable Thermal Conductivity Structures

> Microvascular Systems for Mass/Energy Transport

< Microvascular Autonomic Composites

Carbon Fiber Morphology for Thermal Materials

> New; < Concluded

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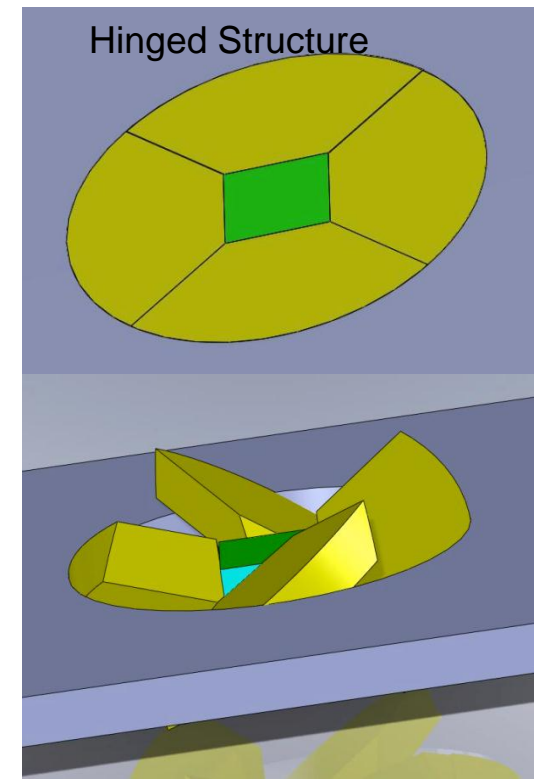
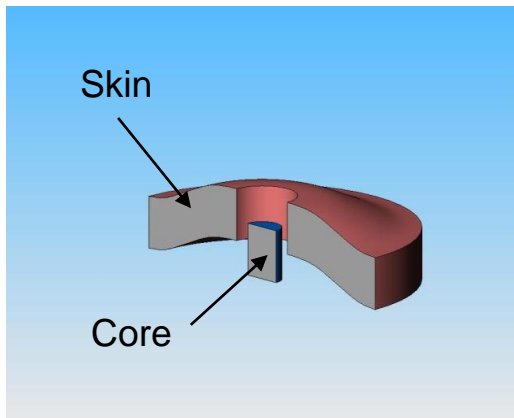
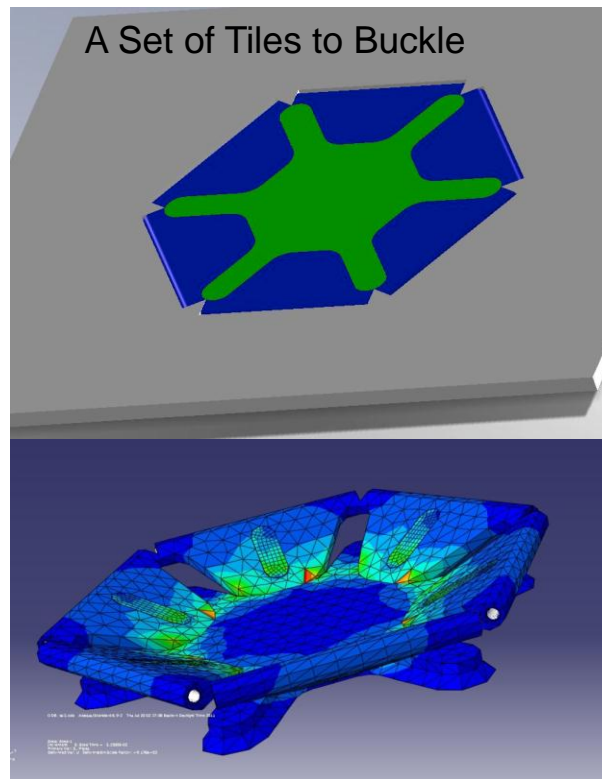
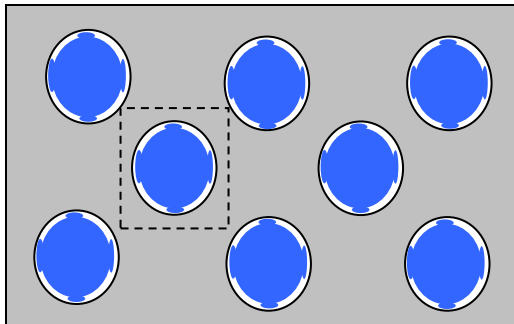
^ YIP; * MURI



PERSPIRABLE SKIN OF CERAMICS (*Mich State U: Kwon*)



- **Approach (I): Deformable materials under thermal loading** (The interference between two distinct materials that has been shrink-fitted opens for cooling; gap is not large enough)
- **Approach (II): A set of tiles to buckle under thermal loading** (Upon heating, the tiles push on the core radially, while shrinking circumferentially, enabling a buckling action)
- **Approach (III): A hinged structure triggered by internal pressure** (The assembly consists of the skin (rectangular part), two half circular tiles, and two axes to provide a rotation)





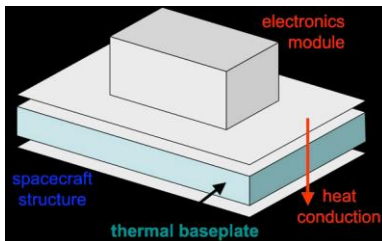
THERMAL BASE PLATE DESIGN

(Penn State: Lesieutre)



Need for Material Systems with Variable Thermal Conductivity

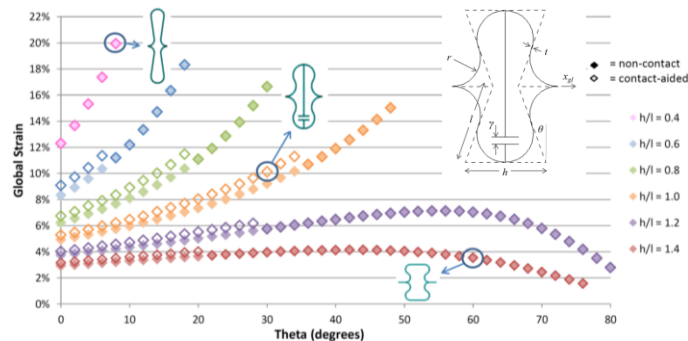
- **Electronic modules** are designed to operate near room temperature and they generate significant heat loads. They are connected to the spacecraft bus structure via a **thermal base plate** which is intrinsically **multifunctional**.
- The thermal base plate transfers **mechanical load** and transfers **heat** away from (or insulates) the electronics module in order to ensure that the electronics do not overheat (or become too cold).



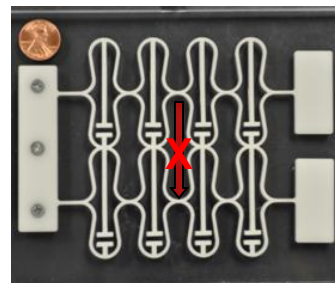
- Active and passive **thermal switches** exist, and passive ones are preferred for low power and complexity.

Cellular Contact-aided Compliant Mechanisms (C3M):

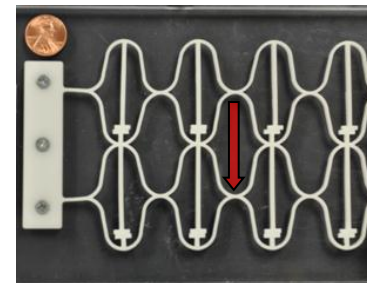
- C3M allow the design of **cellular structures with novel integrated contact mechanisms** that provide **local stress relief** under high loads. They are capable of ultimate strains exceeding 10%, while bulk ceramic materials have high strength, but low strain at failure (0.2-1%).
- Using **multiple materials** (e.g. **ceramic-metal** combination), these contacts also introduce new thermal conduction pathways and provide a novel potential avenue to **passive thermal switches**.
- When the “hot side” of the thermal base plate is **below a threshold temperature**, the base plate is in a **thermally-insulating** state, associated mainly with ceramic parts of the C3M based structure.
- As the temperature of the “hot side” increases **above threshold value**, the C3M based structure expands and **internal contact** is made between conducting members, dramatically **increasing the thermal conductivity** of the base plate. This conductivity is maintained at higher temperatures.



Global strain vs. Cell angle parameter

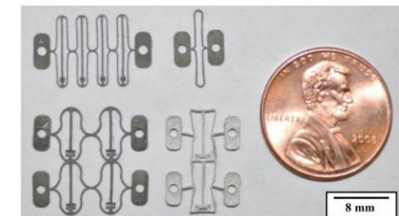


Non-Conducting



Conducting

metal/ceramic parts made by “lost mold, rapid infiltration forming” (LM-RIF) process





2012 AFOSR SPRING REVIEW



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Energy Management for Self-Sustaining Systems
*Actuation & Threat Neutralization;
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Greg Carman (UCLA)
Wonbong Choi (FL Int'l U)
Hugh Bruck (U MD)
Gleb Yushin (GA Tech) ^
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Ioannis Chasiotis (UIUC) *
Michael Durstock (AFRL/RXBN)
Benji Maruyama (AFRL/RXBN)
John Coggin (Prime Photonics) +
Nersesse Nersessian (MAPCo) +
Anuncia Gonzalez (Lynntech) +



2012 AFOSR SPRING REVIEW



NAME: B. A.

BRIEF DESCRIPTION

Basic science
into future

LIST OF SUBJECTS

Fundamental

Life Prediction

Sensing, Failure

Multifunctional

Multifunctional

Self-Healing

Self-Cooling

Energy Materials

Actuation

Engineering

Subject:

Energy Harvesting Textile Composites
Active Structural Fibers for Multif'l Composites
Vibration Suppression and Energy Harvesting
Energy Harvesting Using Electrodynamic Tethers
Environmental Hydrocarbon Harvesting Via CNT
Nanoscale Based Thermal Energy Harvesting
Flexible Battery of Graphene-CNT Hybrid
> Integrated Solar Cells for MAV Wings
< Multifunctional Mg-Li Alloy Nanocomposites
< Energy Harvesting/Storage System Integration

Nanomaterials for Structural Batteries

> Hybrid Energy Harvesting Systems

“

“

> New; < Concluded

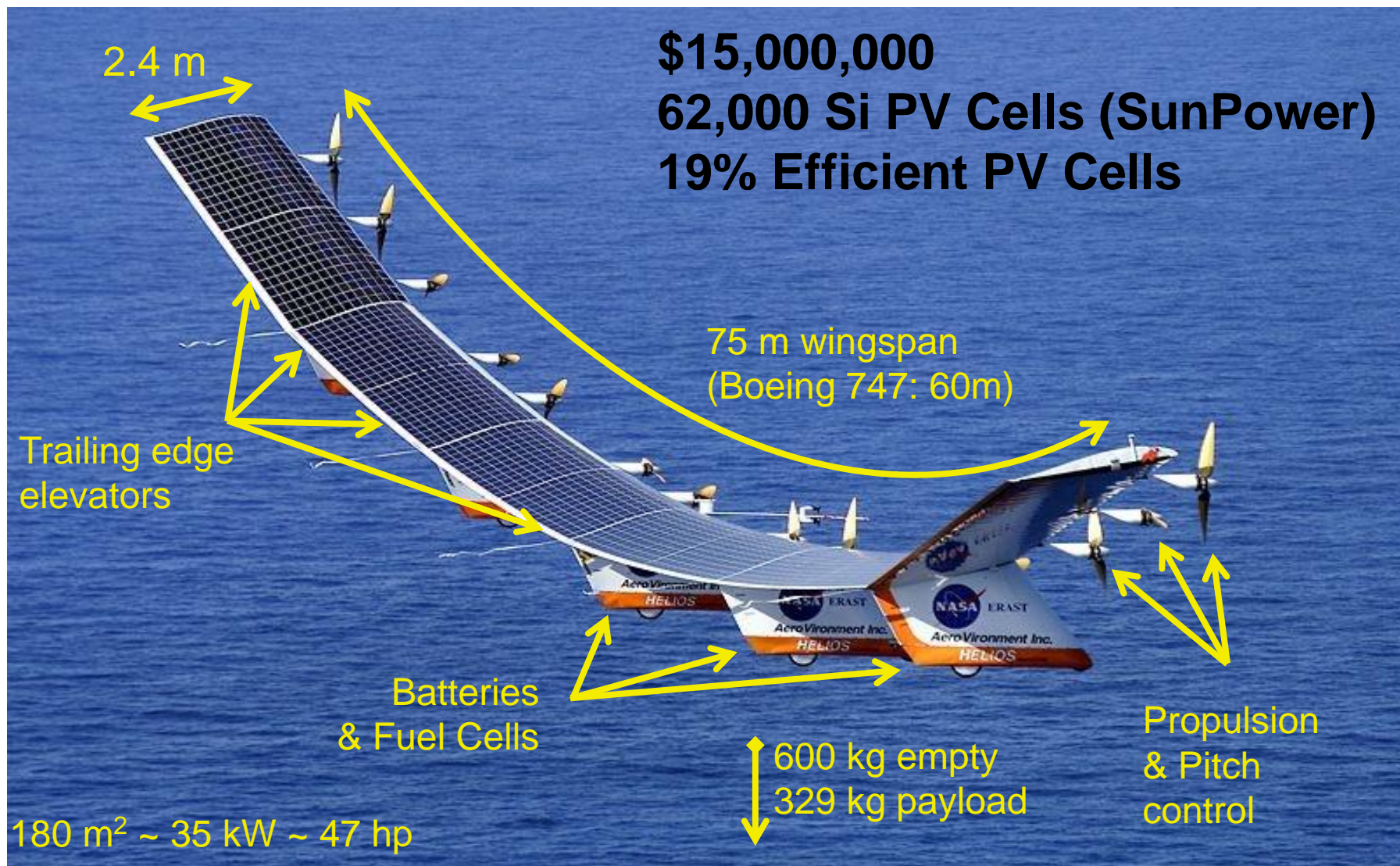
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Anuncia Gonzalez (Lynntech) +

PECASE; ^ YIP; * MURI; + STTR



NASA "HELIOS"

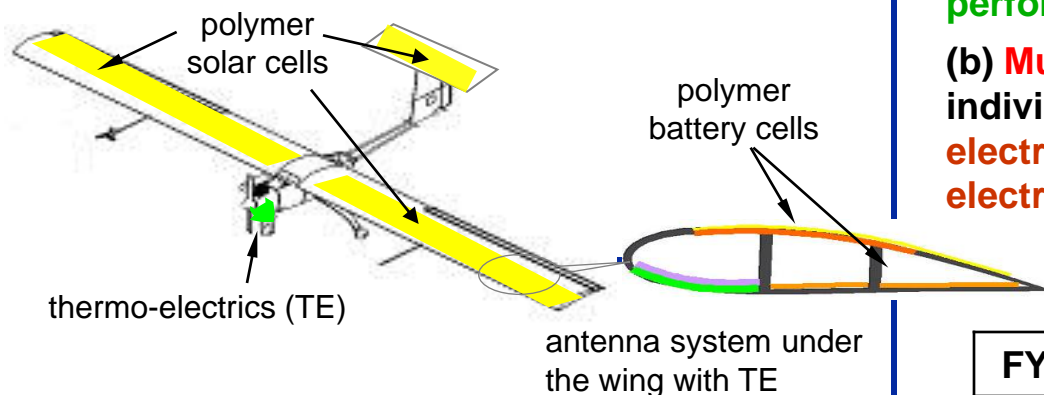


INTEGR'D ENERGY HARVESTING (U WA/U CO/UCLA/VT: Taya)



Objective:

To develop “self-powered” load-bearing structures with **integrated energy harvest/storage capabilities**, and to establish new **multi-functional design rules** for structural integration of energy conversion means.



DoD Benefit:

Self-powered load-bearing structures with integrated energy harvest/storage capabilities will provide meaningful **mass savings** and **reduced external power requirements** over a wide range of defense platforms including **space vehicles**, **manned aircraft**, **unmanned aerial vehicles**, and **ISR systems**.

Technical Approach:

- (a) A combination of experimental and analytical techniques are employed to advance the **efficiency** of the energy conversion means (as an integral part of **load-bearing** structures) and to optimize their multifunctional **performance** and **ability to cover larger areas**.
- (b) **Multifunctional composites** are created with individual layers acting as **photovoltaic/thermo-electric/piezoelectric** power harvesting and **electrochemical** power storage elements.

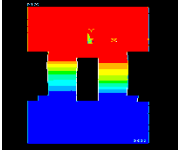
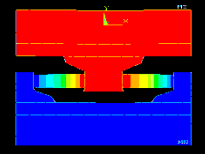
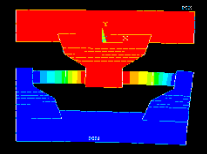
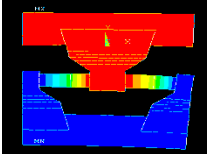
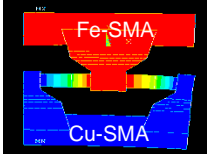
Budget:

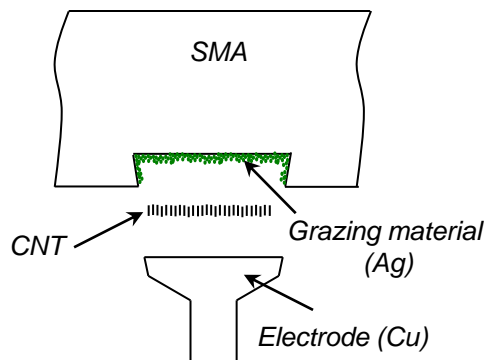
	FY06	FY07	FY08	FY09	FY10	FY11
\$K	693,335	1,169,560	1,180,608	1,219,324	1,179,991	568,571

Major Reviews/Meetings:

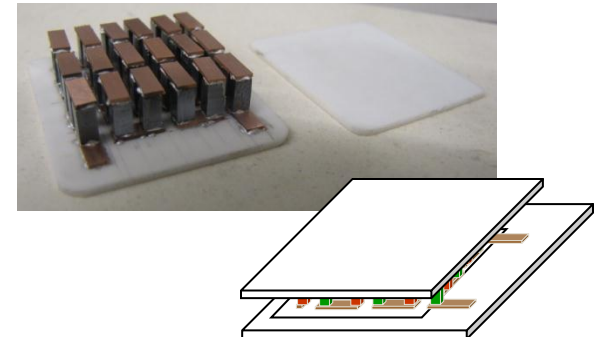
- 29 August 2007: Seattle, WA
- 5 August 2008: Boulder, CO
- 11 August 2009: Blacksburg, VA
- 18 August 2010: Los Angeles, CA
- 5 August 2011: Arlington, VA



TE design Analysis results	Phi TE	Linear TE	Linear TE w/ FGM and shrink-fit (1.25mm)	Linear TE w/ FGM and shrink-fit (2.5mm)	Linear TE w/ FGM and shrink-fit (2.5mm)
					
Generated temperature gap across TE element (deg C)	338	344	344	346	394
Maximum normal stress on electrode (Mpa)	-1100	-1200	-535	-591	-642
Maximum shear stress on electrode (MPa)	146	617	329	311	337
Maximum shear stress on TE element (MPa)	125	71	34	43	56
Power density (W/cm ²)	0.80	0.87	0.87	0.89	1.15
Module efficiency (%)	12.8	13.3	13.3	13.4	14.8

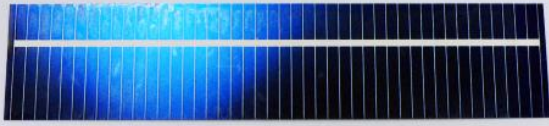



- **n-type:** $\text{Mg}_2\text{Si}_{0.96}\text{Bi}_{0.03}\text{In}_{0.01}$
- **p-type:** $\text{Si}_{0.93}\text{Ge}_{0.05}\text{B}_{0.02}$
- Heat source side: Fe-SMA
- Heat exhaust side: Cu-SMA
- CNT in grazing material gives:
 - ✓ locking Ag
 - ✓ reducing the creep strain



Comparison of Solar Cells for Structural Integration



	Monocrystalline Silicon Solar Cell	Amorphous Silicon Solar Cell
Tensile Loading	Breaks at 0.23 % tensile strain	Works well at 1.6 % tensile strain. Composite laminates breaks around 1.5 % strain.
Fatigue Loading	N/A	Works well at fatigue cycle of 0.3 % strain
Efficiency	23 %	12 %
Price	High (200 um thick c-Si needed)	Low (about 1 um thick a-Si needed)
Sample		

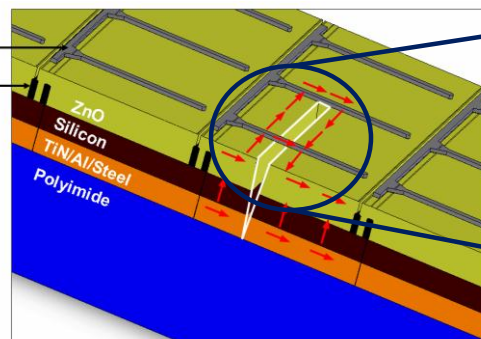
	Cu(In,Ga)Se ₂ Solar Cell	Dye Sensitized Solar Cell
Pros	Highest efficiency among thin film solar cells	Cheapest among thin film solar cells
Cons	Degrades with humidity ; manufacturing generates very toxic gases to the environment.	Unstable efficiency; extremely corrosive

Solar Cells Under Fatigue



Free standing **amorphous Si** solar cells

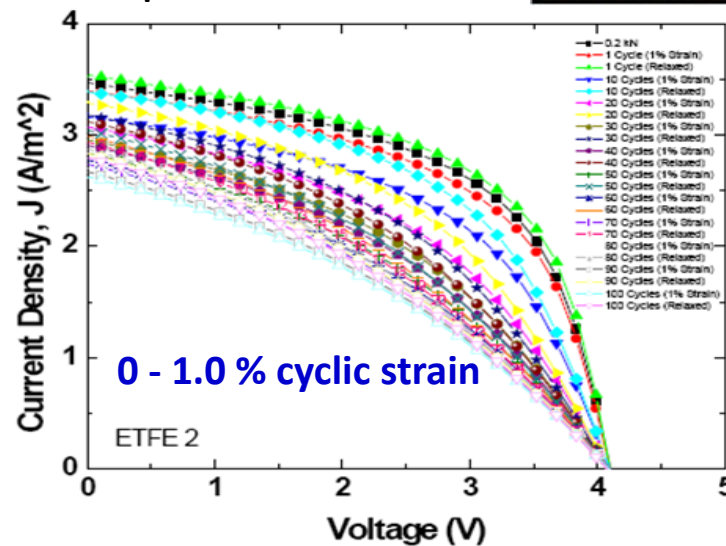
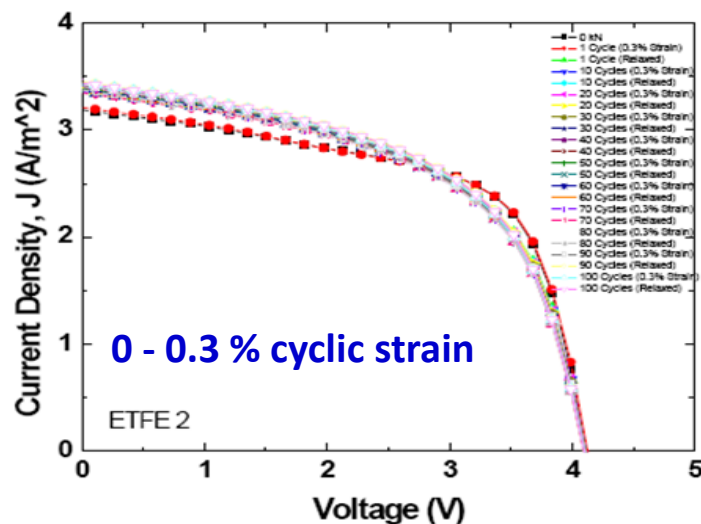
ZnO (~3 μ m)	Device
p-type μ c-Si (~250 Å)	
Intrinsic a-Si (~4000 Å)	
n-type μ c-Si (~150 Å)	
TiN (< 1000 Å)	
Alumimun (~0.3 μ m)	
Stainless Steel (< 1 μ m)	Substrate
Polyimide (~30 μ m)	
Stainless Steel/Al (<1 μ m)	
	Antistatic Layer



→ current path



cracks

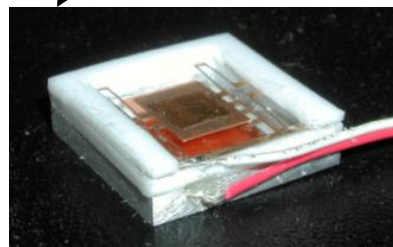
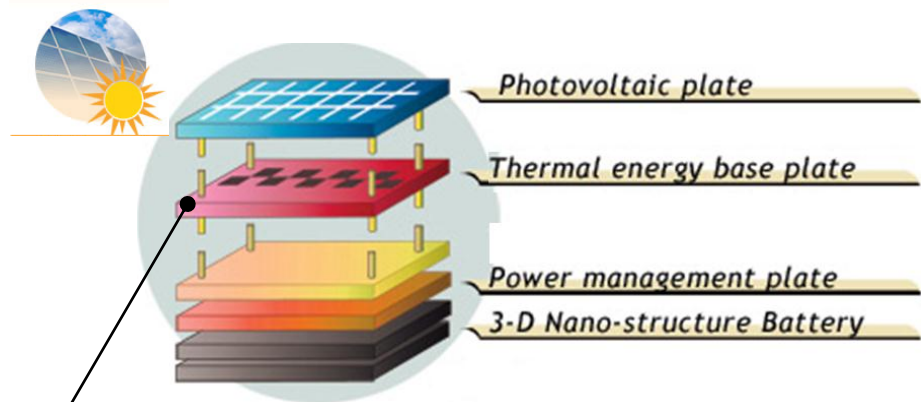




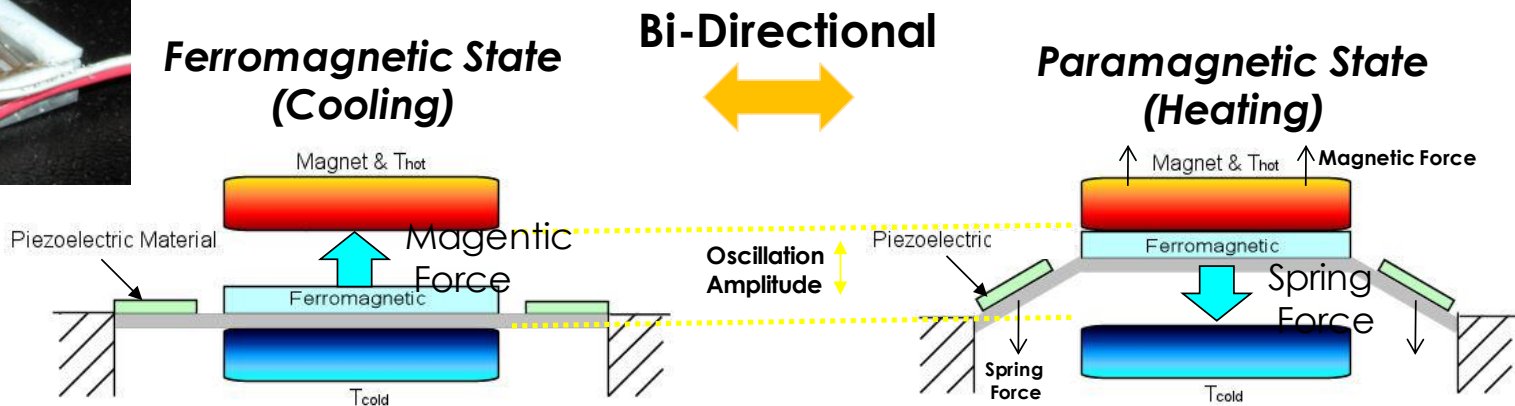
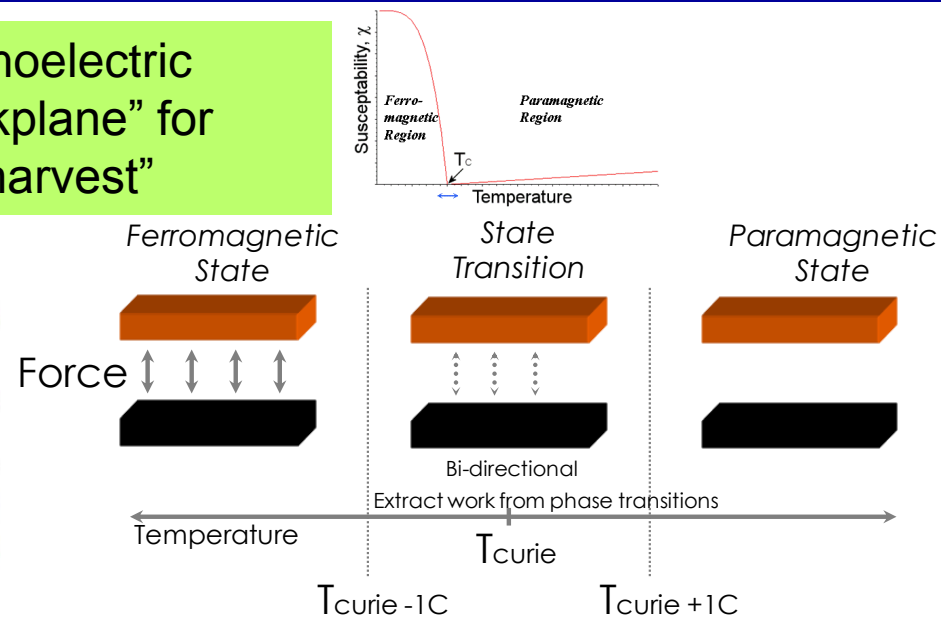
STTR' 10: HYBRID ENERGY HARVEST



- Pairing solar panels with magneto-thermoelectric power generator as “active thermal backplane” for solar panel cooling and “hybrid energy harvest”



magneto-thermoelectric power generator (STTR'07)





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Multifunctional

Self-Healing

Self-Cooling

Energy Management

Actuation

Engineering

Subject:

< **Cellular Shape Memory Structures**

< **Reversible Shape Memory Polymer Composites**

< **Electroosmotically Actuated Shape Change**

Ultra-Maneuverable Bat Technologies

Bio-inspired Design of Reconfigurable Structures

Active Cells for Multifunctional Structures

Morphing CNT Microstructures

Metamaterial Enhanced MEMS

Acoustic Metamaterials w Local Resonance

Macroscale Meta-Materials

Active Materials w Sensory & Adaptive Capabilities

> **Mechano-Responsive Polymer Systems**

Mechanically-Responsive Polymers

Thermally-Activated Reconfigurable Systems

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Greg Reich (AFRL/RBSA)

> **New**; < **Concluded**

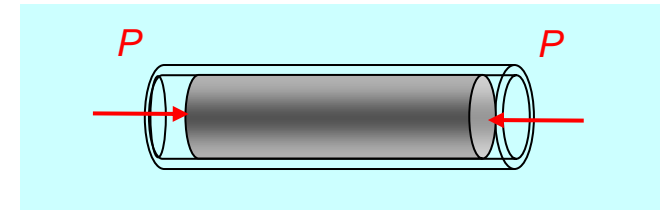
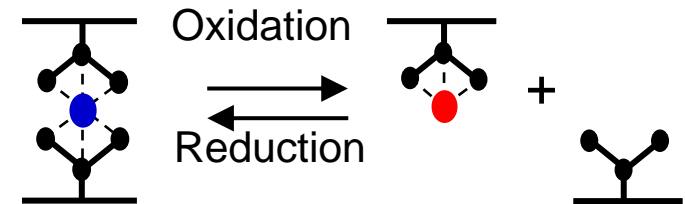
^ **YIP**



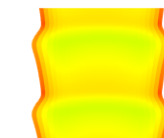
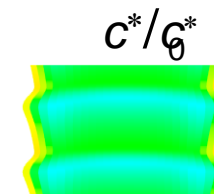
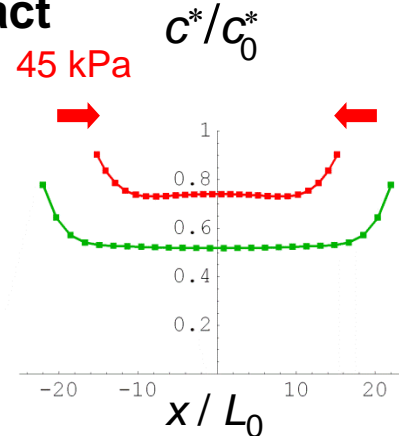
DESIGNING SELF-REINFORCING MATERIALS (*U Pitt: Balazs*)



- Developed model to describe BZ gels with chemo-responsive X-links
 - Modified Oregonator model
 - f – dependent complex formation
 - Time-dependent elastic contribution
- Studied response to steady and periodic compression in 1D model
- Mechanical impact increases X-link density
 - Self-reinforcing material
 - Stiffens in response to impact



V.V. Yashin, O. Kuksenok, A.C. Balazs,
J. Phys. Chem. B 2010, 114(19), 6316.

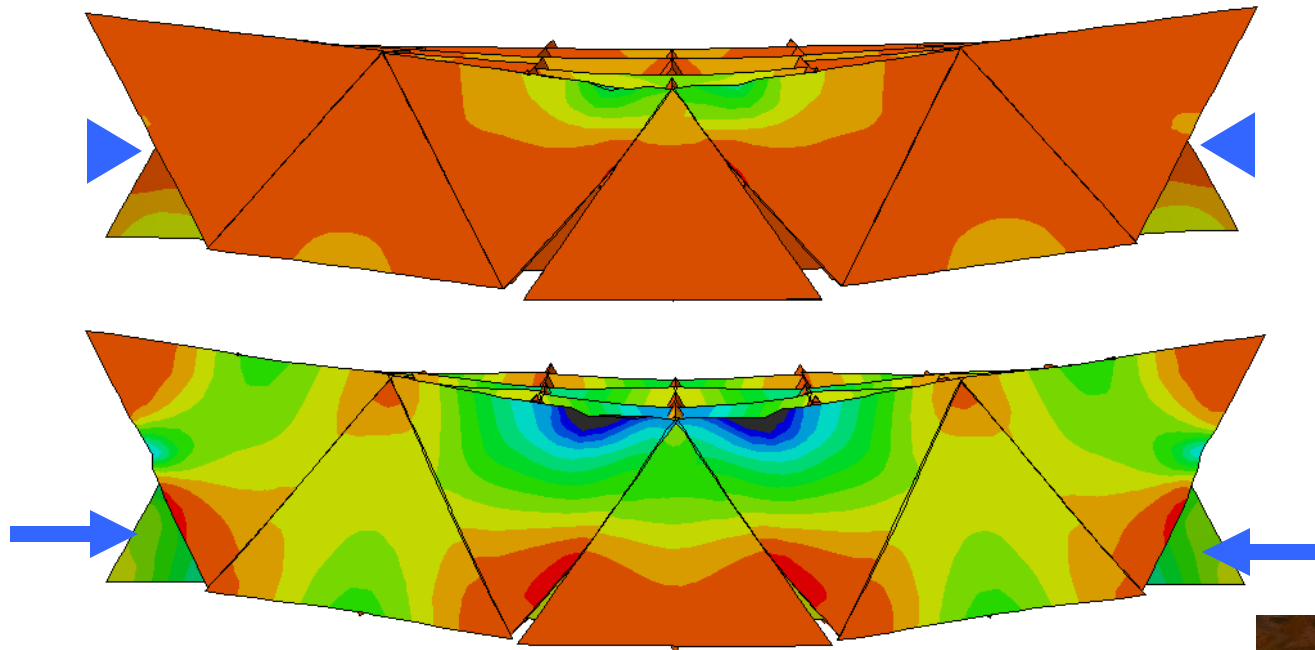


0.511 0.926

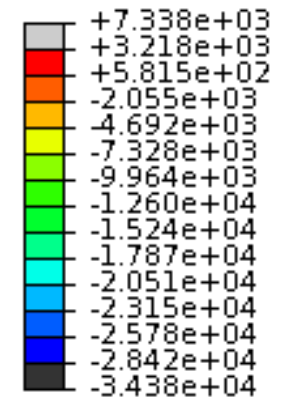




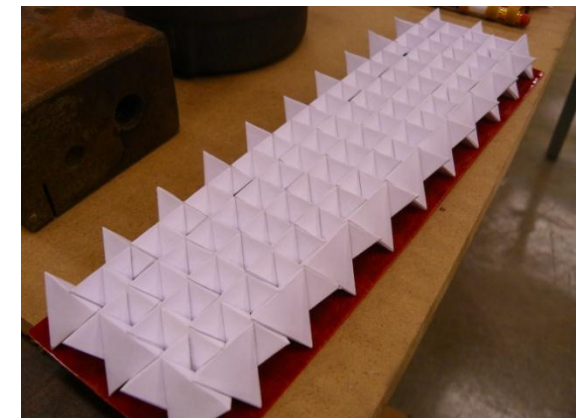
TOPOLOGICAL INTERLOCKING (Purdue U: Siegmund)



In-plane Stress



- Confinement changes translate in change on contact conditions
- Large confinement leads to smaller opening and more resistance to load
- Retain damage tolerance in the high stiffness regime





2012 AFOSR SPRING REVIEW



NAME: *B. L. ("Les") Lee*

BRIEF DESCRIPTION OF PORTFOLIO:

Basic science for integration of emerging mater into future Air Force systems requiring multi-fu

LIST OF SUB-AREAS:

*Fundamentals of Mechanics of Materials;
Life Prediction (Materials & Micro-devices);
Sensing, Detection & Diagnosis;
Multifunctional Design of Autonomic Systems;
Multifunctional Design of Reconfigurable System
Self-Healing & Remediation;
Self-Cooling & Thermal Management;
Energy Management for Self-Sustaining System
Actuation & Threat Neutralization;
Engineered Nanomaterials*

PI's & Co-PI's:

*Jimmy Xu (Brown U)
Erik Thostenson (U Del)^
Frank Ko (U Brit Columbia)*
Jeff Baur (AFRL/RXBC)
Nancy Sottos (UIUC)
Vikas Prakash (Case Western)
Ajit Roy (AFRL/RXBT)
Michael Strano (MIT)
Greg Carman (UCLA)
Wonbong Choi (FL Int'l U)
Gleb Yushin (GA Tech)^
Se-Hee Lee (U CO)*
Michael Durstock (AFRL/RXBN)
A. John Hart (U Mich)
Richard Vaia (AFRL/RXBN)
Ray Baughman (U Texas Dallas)
Nicholas Kotov (U Mich)
Mrinal Saha (OK St U)
Tsu-Wei Chou (U Del)
Yuntian Zhu (NCSU)
Alexander Bogdanovich (NCSU)
Philip Bradford (NCSU)*



2012 AFOSR SPRING REVIEW



NAME: B. A.

BRIEF DESCRIPTION

Basic science
into future

LIST OF SUBJECTS

Fundamental

Life Prediction

Sensing, Detection

Multifunctional

Multifunctional

Self-Healing

Self-Cooling

Energy Management

Actuation

Engineering

Subject:

Thermal Signature Reduction & EMI Shielding
Nanocomposites for Sensing & Actuation
Bio-inspired Intelligent Sensing Materials
Embedded Sensors & Actuators for MAV
Interfacial Self-Healing in Composites
CNT Based Thermal Interface Materials
Carbon Fiber Morphology for Thermal Materials
Environmental Hydrocarbon Harvesting Via CNT
Nanoscale Based Thermal Energy Harvesting
Flexible Battery of Graphene-CNT Hybrid
Multifunctional Mg-Li Alloy Nanocomposites
Energy Harvesting/Storage System Integration
Nanomaterials for Structural Batteries
Morphing CNT Microstructures
Mechanically-Responsive Polymers
Artificial Muscles for Large Stroke & High Force
< Layer-by-layer Processing of CNT Composites
< Hierarchical Structures of CNT Composites
Thin Flexible CNT Composites

> Shear Pressed CNT Sheets for Strain Sensing

> New; < Concluded

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Yuntian Zhu (NCSU)
Alexander Bogdanovich (NCSU)
Philip Bradford (NCSU)

^ YIP; * MURI



CNT YARNS FOR ARTIFICIAL MUSCLES (*UT Dallas: Baughman*)



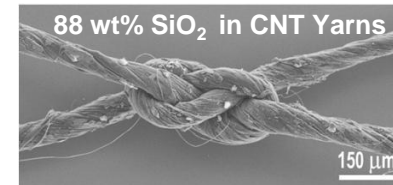
“Biscrolling Nanotube Sheets and Functional Guests into Yarns”, Science 331, 51 (2011).

- **Weavable, sewable, braidable** and **knottable** carbon nanotube (CNT) **yarns** that can contain over 92 wt% of **functional guest powders** are made by twist insertion in a guest/CNT sheet stack.
- Demonstrated use of these “**biscrolled**” **yarns** as **battery/fuel cell electrodes** and as **superconductors**.

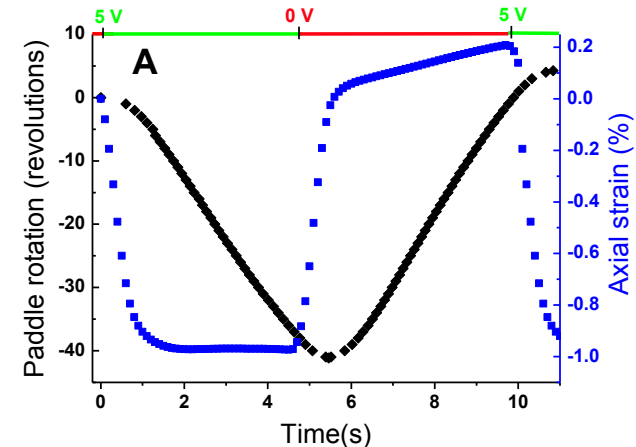
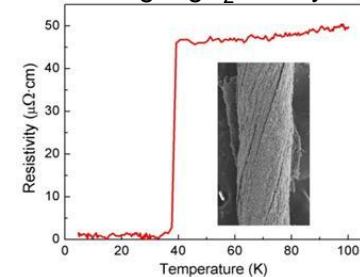
“Torsional Carbon Nanotube Artificial Muscles”, Science 334, 494 (2011).

- **Tensile** and **torsional actuation** results from **yarn volume change** caused by **ion influx** to compensate **electronically injected charge**. Torsional rotation per actuator length was 1000 times that of prior-art torsional actuators.
- The actuating yarn electrode can accelerate an 1800 times heavier paddle up to 590 revolutions/min in 1.2 s and provide similar gravimetric torque and mechanical power generation per yarn weight as for large electric motors. **Microfluidic** application was demonstrated.

Biscrolling process



Superconducting MgB₂/CNT yarn



Torsional and tensile actuation for electrochemically driven twist-spun yarns



MIRAGE EFFECT OF CNT SHEET (UT Dallas: Baughman)



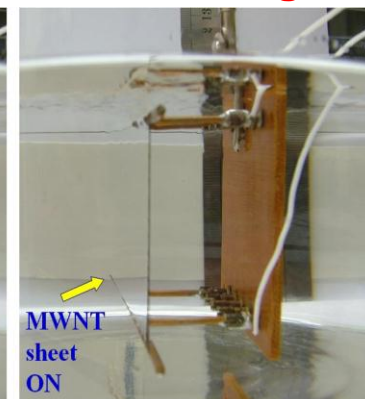
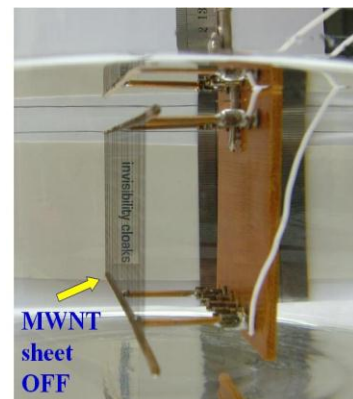
*"Mirage Effect from Thermally-modulated Transparent Carbon Nanotube Sheet",
Nanotechnology **22**, 435704 (2011).*

- **Electrically conducting sheets**, which are drawn from forest-like arrays of carbon nanotube (CNT), can be used as **transparent**, rapidly **thermally switchable mirage cloaks** and as inexpensive optical scanners.
- This **invisibility for light** oblique to the CNT sheet is caused by the **mirage effect**, in which a thermally generated **refractive index gradient** bends light away from an object.
- Extremely **low thermal capacitance** and **high heat transfer ability** of CNT sheets enable high frequency modulation of sheet temperature over a wide range, thereby providing a sharp, rapidly changing gradient of refractive index in surrounding liquid or gas.

*Time Magazine's issue
on 50 Best Inventions
of 2011*



Cloaking





BIO-INSPIRED SYSTEMS: BEYOND CURRENT VISION



VISION: *EXPANDED*



Biomimetics

Design for Coupled
Multi-functionality

Nano-materials

Multi-scale
Model

Micro- & Nano-
Devices

Manufacturing Sci

Neural Network &
Information Sci

AUTONOMIC AEROSPACE STRUCTURES

- Sensing & Precognition
- Self-Diagnosis & Active Response
- Self-Healing
- Threat Neutralization
- Self-Cooling
- Self-Powered

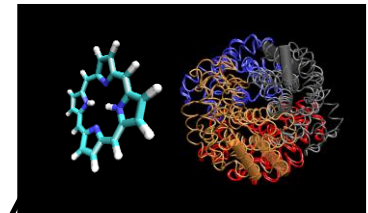
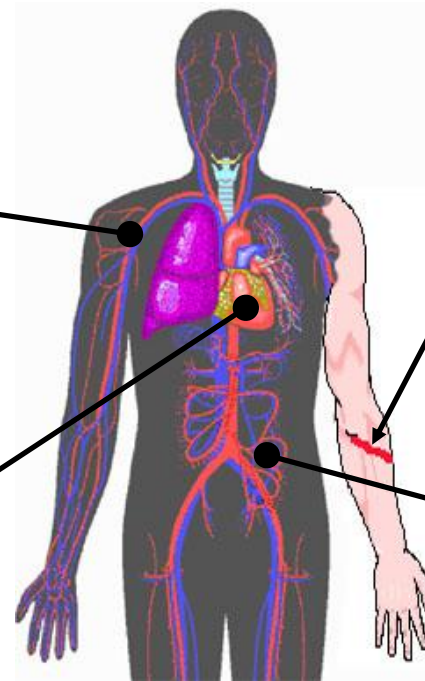
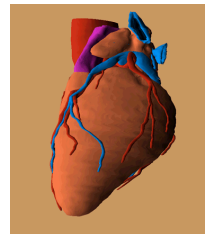


FUNCTIONS OF INTEREST



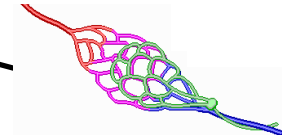
Self-Regulating Function

Active Regulation



Self-Generating Function

Mesoporous Networks



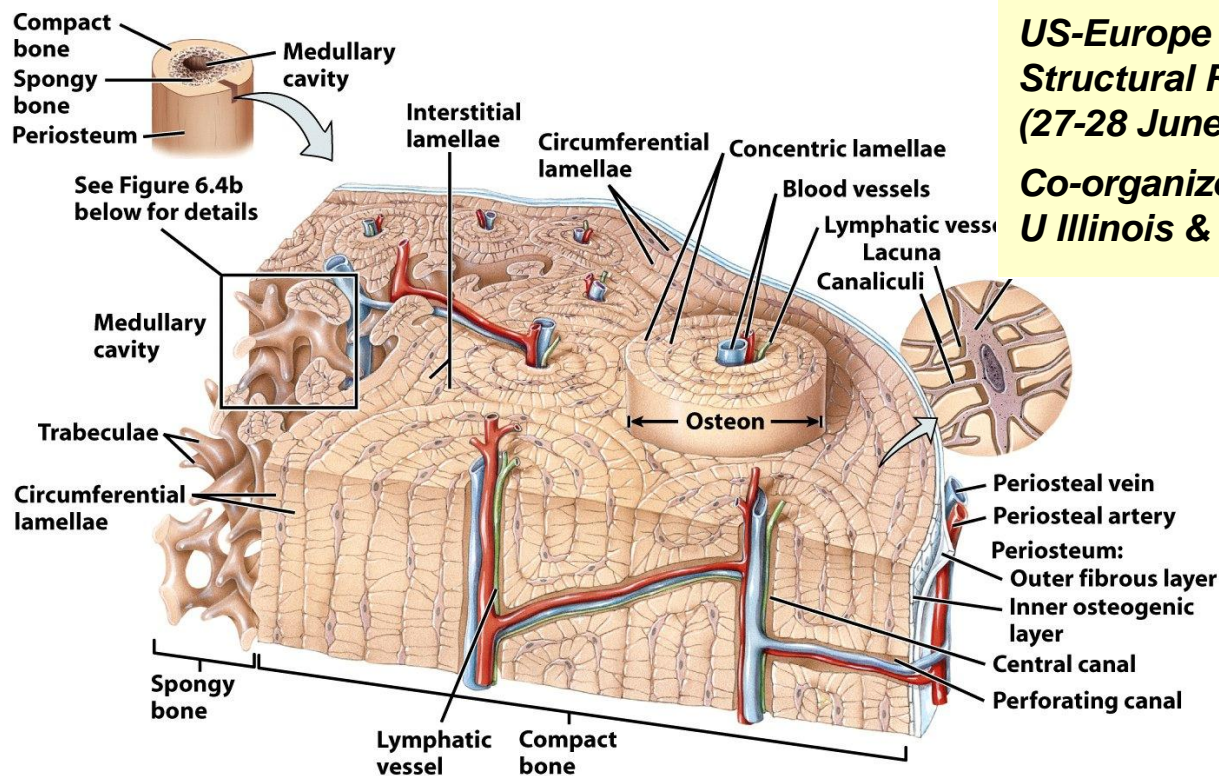
11



Design by Nature: BONE REMODELING



Resorption vs **Ossification**; 4~20% renewal per year;
Subjecting a bone to **stress** will make it **stronger**



*US-Europe Workshop on
Structural Regeneration
(27-28 June 2012, Venice)*

*Co-organized by AFOSR, ARO,
U Illinois & Max Planck Inst.*

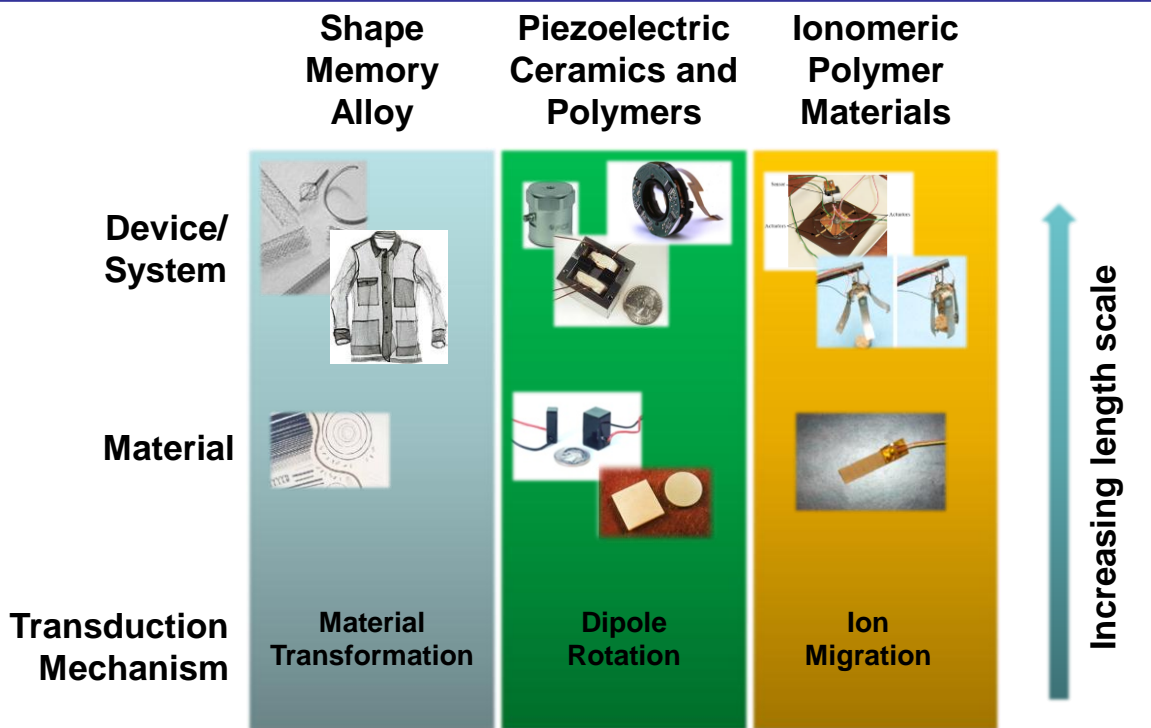
Fig. 6-4a Anatomy and Physiology: From Science to Life © 2006 John Wiley & Sons



ENGINEERED DEVICES: *BEYOND CURRENT VISION*



Traditional Transducer Materials



Center for Intelligent Material Systems and Structures
at Virginia Polytechnic Institute and State University

donleo@vt.edu



ENGINEERED DEVICES: *BEYOND CURRENT VISION*



Traditional Transducer Materials

Device/
System

Material

Transduction
Mechanism



The question we are studying ...

*How can we use
biomolecules to
make completely
new types of
materials for
**engineered
devices**?*

Device/
System

Material

Transduction
Mechanism

Sensors,
Energy
Capture and
Conversion,
Color Changes

Durable,
Robust,
Easy to
Manufacture

Channels,
Pumps,
Transporters

Increasing length scale



donleo@vt.edu



SUMMARY



- The program is fully focused on the establishment of advanced **multi-functional** aerospace structures.
- A major progress has been made in pursuing a new **vision** for **autonomic/reconfigurable systems** and providing research support for baseline multifunctional materials and microdevices.
- Multi-disciplinary research initiatives are concluded successfully for **“self-healing,” “structurally integrated energy harvest/ storage capabilities,”** “energy harvesting from aerospace environment,” and **“load bearing antennas.”**
- Three initiatives are in progress for **“neurological system inspired sensory network”** (MURI '09), **“reconfigurable multi-functional structures”** (DCT'09) and **“high-rate deformation”** (CoE'12).
- New initiatives are planned for **“biomolecular autonomic material systems,” “hybrid energy harvesting”** and **“neutralization of threats”** in collaboration with AFRL/AFOSR colleagues.